THE MILLENNIUM ARECIBO 21-CM ABSORPTION LINE SURVEY: EXTOLLING THE ANALYSIS PROCEDURES

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ABSTRACT

We have recently completed the analysis of a survey of the HI line in emission/absorption against 79 radio sources. Our CNM temperatures are about half those of previous authors and we find a substantial quantity of thermally unstable WNM. These results are somewhat controversial. Here we discuss the analysis procedures to illustrate explicitly why the results are reliable.

Our full papers (Heiles & Troland 2002a, 2002b) discuss our analysis procedures and results in complete detail. The main observational results are

- The Cold Neutral Medium and Warm Neutral Medium (CNM and WNM) are physically distinct components, existing in the ratio $\sim 40 : 60$.

- Previously-derived CNM spin temperatures are typically too high by a factor of two; our CNM temperature histogram peaks at about 40 K. The difference arises mainly from our including a proper radiative transfer treatment.

- About 50% of the WNM has upper limits to the kinetic temperature T_{kmax} in the thermally unstable region 500 to 5000 K. These are derived from line widths, which are in turn derived from Gaussian components.

The last item is particularly important because it violates the cornerstone of most ISM models, such as McKee and Ostriker (1977), that the WNM's temperature is in steady-state equilibrium between microscopic heating and cooling processes. However, our T_{kmax} values come from Gaussian-fit line widths. Because of the difficulties with Gaussian fitting our results have been criticized as being arbitrary, capricious, subjective, nonunique, and of doing "the field of ISM physics great damage". Consequently, it seems worth spending our limited space illustrating our fitting process to show that there is, in fact, little room for doubt in the WNM Gaussians.

1.   OBTAINING THE OPACITY AND EXPECTED HI PROFILES

One can derive spin temperature T_s from emission-absorption observations because the opacity $\tau(\nu)$ depends on T_s differently than the brightness temperature $T_B(\nu)$ does. Naively, one

makes one ON-source and one or more OFF-source observations. One combines the off-source observations to produce the expected profile $T_{exp}(\nu)$, which is the $T_B(\nu)$ that would be seen at the source position if the source were magically turned off. Both $\tau(\nu)$ and $T_{exp}(\nu)$ are affected by HI structure on the sky; these uncertainties are a major item.

For each source we observed a grid of 16 OFF-source positions, plus the ON-source position. This allows us to expand the observed brightness temperature $T_B(\nu)$ in a second-order two-dimensional Taylor series around the source position and to derive the following quantities, *plus their uncertainties*:

1. The opacity profile $\tau(\nu)$.

2. The expected profile $T_{exp}(\nu)$.

3. The first-derivative profiles $\frac{\partial T_B(\nu)}{\partial \alpha}$ and $\frac{\partial T_B(\nu)}{\partial \delta}$ (α is right ascension and δ is declination).

4. The second-derivative profiles $\frac{\partial^2 T_B(\nu)}{\partial \alpha^2}$, $\frac{\partial^2 T_B(\nu)}{\partial \alpha \partial \delta}$, and $\frac{\partial^2 T_B(\nu)}{\partial \delta^2}$.
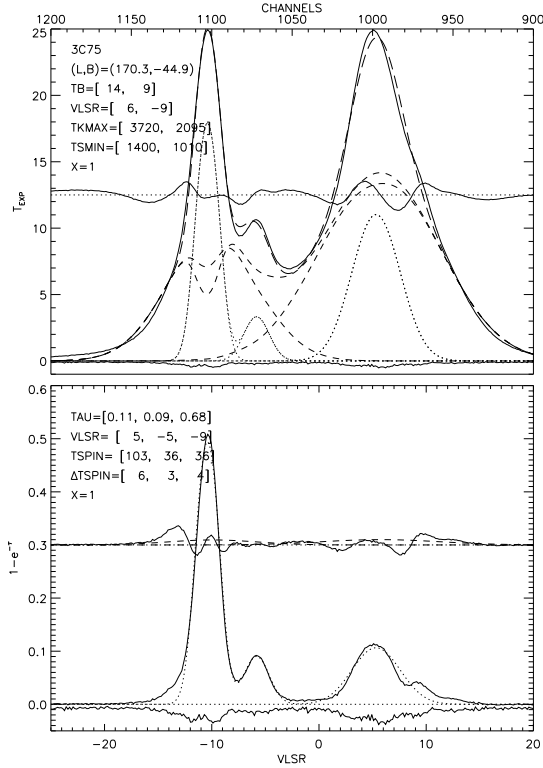

Fig. 1.— Two-panel plot for 3C75. For the complete description, see the text.

Figure 1 exhibits results for 3C75. In the top panel, the solid line profile extending above zero is $T_{exp}(\nu)$. The dashed curves show the observed emission from each individual WNM Gaussian, including absorption by the CNM, and the heavy dashed curve shows the totality of WNM fitted Gaussians. The dotted curves show the intrinsic emission from each individual CNM component, and the heavy dots the observed emission of all CNM components including absorption from the CNM components that lie in front. The solid line near mid-profile-height is the residuals of the data from the fit. The solid line profile extending below zero is the (negative of the) uncertainties in $T_{exp}(\nu)$. The annotation shows the properties of the WNM Gaussian components.

In the bottom panel, the solid line profile extending above zero is the opacity profile $[1 - e^{\tau(\nu)}]$. The dotted curves show each individual CNM opacity Gaussian and the heavy dots show the opacity sum of all the CNM Gaussians ($[1 - e^{-\sum \tau(\nu)}]$. The solid line near mid-profile-height is the residuals of the data from the fit; the dashed line shows the contribution to opacity from each WNM component assuming that its temperature is T_{kmax}. The solid line profile extending below zero is the (negative of the) uncertainty in the opacity profile. The annotation shows the properties of the CNM Gaussian components.

2.   THE GAUSSIAN ANALYSIS PROCEDURE

We choose 3C75 as an example because both the opacity and expected profiles are fairly complicated, yet the fits are unambiguous. There are many sources with less complicated profiles that are fit with fewer components. Of the 79 sources, 58 have two or WNM fewer components.

In the fitting process we first fit the opacity profile with the fewest number of CNM Gaussian components required to make the residuals, on the middle line, comparable with the uncertainties, the negative-going profile at the bottom. For 3C75 this requires three CNM Gaussians, one for each of the major peaks. They are unambiguous: one could certainly not fit fewer. One could include one or more additional components, but this is not required in view of the uncertainties. In the main papers we show that this arbitrariness does not affect derived spin temperatures.

We next perform a least squares fit on $T_{exp}(\nu)$. The parameters include one spin temperature for each CNM component; emission from an arbitrary number of WNM components; the ordering of the CNM components along the line of sight; and the fraction of WNM that lies behind the CNM components. These last two are required because the CNM components absorb emission from WNM that lies behind them, and each CNM component absorbs emission from the CNM components that lie behind it.

It is important to note that the CNM emission, shown by the dotted lines on the top panel, is almost always narrower than the total emission. This highlights the *requirement* for WNM emission that is both broader than the CNM and, also, produces no detectable absorption. This width difference means that:

- The spin temperatures depend mainly on the $T_{exp}(\nu)$ intensity *within* the velocity ranges covered by the dotted-line CNM opacity Gaussians.

- The properties of the WNM Gaussians are determined mainly by the $T_{exp}(\nu)$ profile shape lying *outside* the velocity ranges covered by the dotted-line CNM opacity Gaussians.

In this case of 3C75, we derive upper limits to WNM kinetic temperature $T_{kmax} = 3720$ and 2095 K; both are in the thermally unstable range. Looking at the $T_{exp}(\nu)$ profile, it is clear that there is no way to obtain *wider* WNM Gaussians; the WNM widths are constrained by the portions of the emission profile that lie outside the dotted CNM emission. One can obtain *narrower* WNM Gaussians in two ways:

1. Include a very broad, weak Gaussian to sit underneath the main emission profile. This would eliminate the systematic residuals in the profile wings and produce a better fit. We included such a component for many sources; indeed, for most sources with two WNM components, one of the components is usually such a broad, weak pedestal.

2. Fit a larger number of narrow WNM Gaussians to $T_{exp}(\nu)$. One can often replace a single-Gaussian fit by more narrower Gaussians. However, this violates the philosophy of using the minimum number of free parameters. Moreover, with more narrower WNM components, the WNM temperatures would decrease and their associated opacities would increase; given the uncertainties in $\tau(\nu)$ there is some room for this, but not much.

In this case, then, we conclude that WNM lying in the unstable temperature range is undeniable. Similar conclusions apply in most cases. Some sources have less unambiguous fitting results, but we always attempt to be "reasonable" and this philosophy leads to the statistics that we quote in the abstract and introduction.

REFERENCES

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